Drying technologies for an integrated gasification bio-energy plant

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Abstract

Forced drying of the biomass feedstock is nearly always necessary in an Integrated Gasification Bio-energy Plant (IGBP), and a dryer can represent the highest capital cost item in the pre-treatment section of such a plant. Despite this, there has been relatively little attention paid to the selection and performance of such processes. This review first considers the general requirement for feedstock drying in an IGBP. Brief discussion follows of the theory of evaporative drying, and of the classification of dryer types. The characteristics of biomass feedstocks and IGBP's of relevance to the drying process are then discussed. Suitable dryer types for an IGBP are then identified and described in detail, with performance data for the drying of biomass feedbacks provided where available. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

1.1. The requirement of drying

Feedstocks for an Integrated Gasification Bio-energy Plant (IGBP) are required in the form of loose particulate solids, derived typically by chipping either woody biomass such as residues from forestry operations or purpose-grown short rotation coppice (SRC), or herbaceous biomass such as purpose-grown miscanthus

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or reed canary grass. Such material can have moisture contents ranging from 15 to over 60% (wet basis, w/b) at the point of harvest, depending on the material type, the growing location and the time of year. A value of 50% w/b is often quoted as typical for woody material at harvest under European conditions [1], whereas a herbaceous crop such as miscanthus might be expected to have a content of nearer 30% w/b or less under similar conditions [2].

Natural drying may occur during storage, the degree again depending on the material type and location, the form the material is stored in, the initial moisture content and whether the store is in the open or enclosed. In the present case where crops would be harvested annually in the winter but would be required on a continuous basis at the conversion plant, up to a full year's storage may be necessary. At the end of the summer, a woody crop might have dried naturally from a moisture content of 55% w/b to as low as 30% w/b [3]. However, during operation in the spring, the storage period will have been far shorter and the moisture content correspondingly higher. The conversion plant might therefore expect to receive feedstock with moisture content in the range 30 to 60% w/b in the case of woody material, and 15 to 40% w/b in the case of herbaceous material.

Biomass gasification processes require the time-averaged moisture content of the feed to be in a certain range, depending on the technology, although sizeable variations in moisture content from particle to particle are not likely to be a problem provided the feed is well mixed. Conventional downdraft gasifiers tend to require close control of moisture content somewhere in the range 10 to 20% w/b [4,5] for reasons of temperature control—any higher and the reactor temperature is too low, any lower and slag formation becomes a problem. Updraft gasifiers on
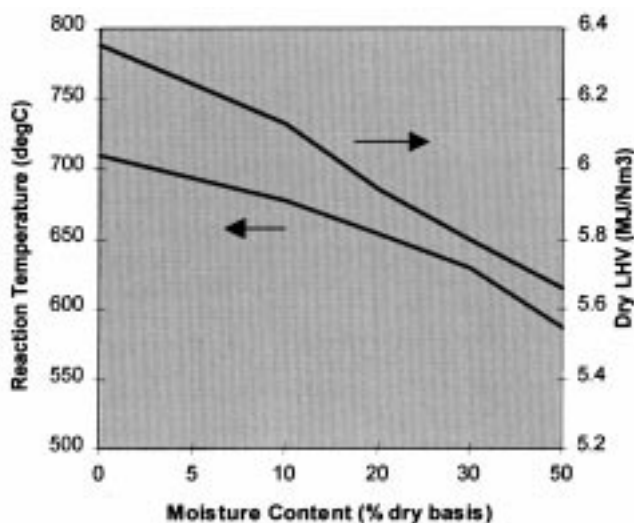

Fig. 1. Effect of feed moisture content on an idealised gasifier.

the other hand can tolerate average moisture contents of up to 50% w/b [4] because of the effective pre-drying that takes place. In all gasifier types, however, an increase in the average moisture content of the feed results in a greater energy requirement for evaporation and a correspondingly lower reaction temperature, which in turn results in a poorer quality product gas with increased levels of tar and a lower overall conversion efficiency (as illustrated in Fig. 1, from model calculations of an idealised gasifier operating under equilibrium conditions). The moisture content of the product gas will also be greater, presenting an increased waste water treatment burden if this water has to be removed prior to use of the gas in an engine or turbine.

In an IGBP therefore, it is usually necessary to dry the feed to some extent at some point between reception and delivery to the reactor.

Forced or assisted drying requires a supply of energy which can be large, and the provision of suitable equipment which can be expensive. It is therefore clearly in the interests of the plant designer to attempt to maximise the efficiency of the drying process while at the same time minimising the capital outlay. Unfortunately greater efficiency is often associated with greater capital cost. The impact of the drying operation on overall plant efficiency can however be reduced by integration, making use of surplus energy streams within the process. If there are competing uses for those energy streams, as is the case in combined heat and power (CHP) schemes, then a further dimension is added to the optimisation process necessary to specify the extent of drying required and the means to achieve it.

There are many methods of drying available, reflecting the wide range of drying tasks encountered in industry. Often, a number of different technologies would be suited to the drying of a particular material, and the final choice is made after careful consideration of operational and economic factors specific to the application. This is certainly true of IGBP feedstocks. The present review is concerned with drying technologies where water is removed by evaporation. Mechanical de-watering techniques (e.g. rams, centrifuges) are available, but are designed for very wet materials such as slurries and pastes which are easily compacted or deformed, and they cannot generally achieve moisture contents below about 55% w/b [6]. Even considering evaporative techniques alone, however, the range of options is vast, and classification of evaporative dryers is a substantial task in itself (see Section 3). It is important therefore in any review to define scope at an early stage.

1.2. Purpose and scope of review

Considering that the dryer can represent the highest capital cost item in the pre-treatment section of an IGBP [7], there has been relatively little attention paid to the selection and performance of the drying process. This review therefore seeks to give a brief general discussion of drying theory and evaporative dryer technologies, and then to describe and evaluate in detail the technologies available for drying of IGBP feedstocks.

The main purpose here is to promote the efficient integration of drying into an IGBP, so as to improve overall efficiency and reduce cost. The review therefore limits itself to evaporative drying technologies for loose particulate solids of a size suitable for either a fixed or a fluid bed gasifier (the most common types), where the primary source of energy for the dryer is thermal energy obtained from some other point in the IGBP process. This energy can be and usually is supplemented by some electrical energy in the drying process, usually in modest quantities but sometimes substantially as with those steam-drying technologies using electrically-driven mechanical vapour re-compression (MVR), in which the outlet steam is compressed to a higher temperature and then used to heat the steam drying medium via a condensing heat exchanger [8].

2. The evaporative drying process

Here a brief overview of evaporative drying theory is given, with particular reference to drying of loose particulate solids. Emphasis has been given to aspects which are of relevance in the understanding of why dryers are designed in the way they are, and on what basis they should be selected. For greater detail the reader is referred to the many texts in the literature dealing with the theory of drying [9–12], probably the most relevant of which is that of Keey [12].

The evaporative drying process for solids can be thought of as two simultaneous processes, one a heat transfer process in which heat is transferred to the wet solid in order to evaporate the liquid, and the other a mass transfer process in which liquid or vapour moves within the solid and vapour leaves the solid surface (Fig. 2).

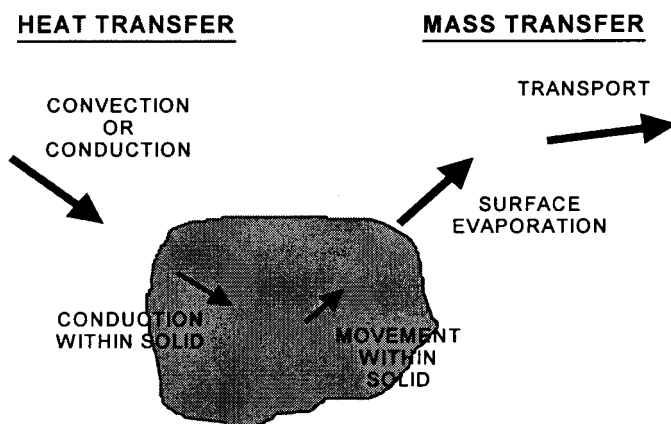In the technologies considered here, heat transfer occurs predominantly by

Fig. 2. Processes involved in evaporative drying.

convection or conduction or a combination of the two, with radiation playing a negligible part. Dryer types can be distinguished according to which of these is the principal mechanism of heat transfer, as will be discussed in Section 3. It is clearly important to maximise contact between the drying medium and the material being dried, and a great deal of attention has been paid to this aspect in the evolution of the wide range of dryer types in existence.

Mass transfer takes place by two general mechanisms; internal movement of liquid or vapour through the wet solid by processes such as capillary flow and diffusion, and external movement of vapour away from the material surface. The former depends on material structure and properties, as well as moisture content; the latter on external temperature and pressure, material surface area, Reynolds number, and humidity if air or some other inert gas is being used as the transport medium. Both mechanisms can limit the overall drying rate, depending on the stage of the drying process.

2.1. The drying medium

The drying medium refers to the gaseous medium surrounding the drying solid as it dries, and can therefore either be pure vapour (in this case steam) or a mixture of vapour and a non-condensable gas such as air or combustion products. In convective systems, the drying medium is also the source of heat; in conductive
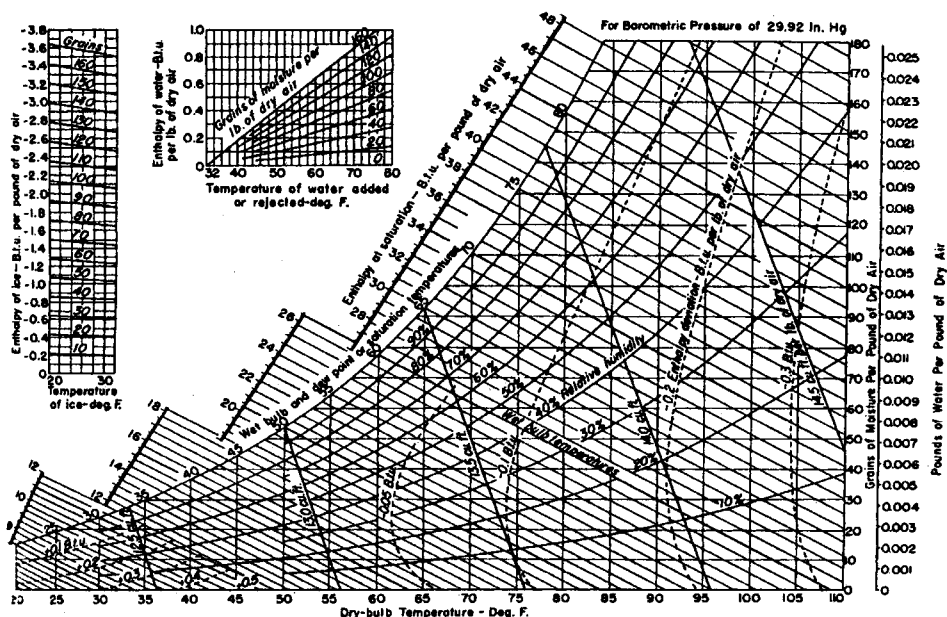

Fig. 3. Psychrometric chart, medium temperatures.

systems it represents only the evolved moisture, in some cases combined with a transport gas.

In the case of a pure vapour medium, the medium must be superheated for further drying to take place—otherwise the evaporated moisture would simply re-condense. That is to say, the medium must be at a temperature greater than the boiling point of the moisture at the pressure of the system (see Section 2.4). Provided this condition is met, there is no limit to the carrying capacity of the medium. In the case of steam, properties are readily obtained from standard tabulations.

For mixtures of gas and vapour, the principles of psychrometry apply. Again, the mixture must be below the saturation point for further evaporation to take place, so the saturation point represents an ultimate limit for a given drying situation if the dry bulb temperature is below the liquid boiling point. If the dry bulb temperature remains above the liquid boiling point, the moisture carrying capacity is infinite. Properties of air–water mixtures are also readily obtained from tabulations, or from a psychrometric chart (Fig. 3). Where the gas is combustion products rather than air, small corrections may be necessary.

The major advantage of a pure steam drying medium is that the steam product may be utilised [13], either externally by operating the drying process at elevated pressure and exporting the steam product to the external point of use, or internally by using MVR to return some of the steam enthalpy to the drying process [8]. MVR involves compressing the extracted vapour in an electrically-driven compressor, and then effecting heat transfer with the drying steam via a condensing heat exchanger so that the latent heat is returned to the process (Fig. 4). The process has however to be suitably configured for this to be possible. MVR is impractical for mixtures of vapour and air or other gases, and is also highly susceptible to particulate contamination of the vapour which can cause compressor damage. Indeed the viability of MVR for drying has been constrained in the past by the availability of suitable compressor technology [14], although this is improving.
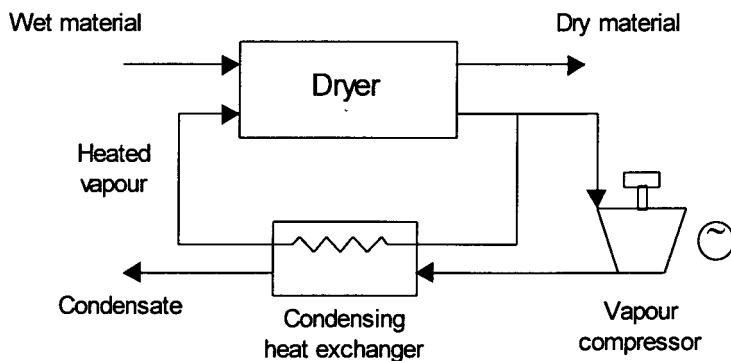

Fig. 4. Mechanical vapour recompression drying.

2.2. Periods of drying

If a sample of the material to be dried is exposed to the drying medium at controlled constant conditions, and the rate of moisture loss from the sample is plotted against time, the resultant curve takes the general form shown in Fig. 5 [15]. There is an initial period A–B during which the material heats up and the drying rate increases. This is followed by a period of constant drying rate B–C, the constant rate period, during which movement of water through the solid is sufficiently rapid to maintain saturated conditions at the surface, and evaporation is equivalent to that from a body of water. Finally, internal movement of water can no longer maintain saturated conditions at the surface and a period of falling drying rate C–D is entered, the falling rate period. This period is often divided into two, a period where the material surface is partially wet and neither mechanism dominates fully, followed by a period where the material surface is completely dry and movement of water through the solid is fully rate limiting. Clearly, drying to low moisture levels implies progressively longer drying time (and therefore greater dryer capital cost) the lower the final moisture level, and it is most important in these situations to avoid drying beyond the requirements of the subsequent process or use.

Drying rates are very difficult to predict for a given material, particularly for the falling rate period, and experimental methods under controlled conditions are usually required to determine them. One of the key variables to be determined is the moisture content at which constant rate drying finishes and falling rate drying begins—the so-called critical moisture content. This is a function of many variables, including material structure, material thickness and initial moisture content. In some materials a constant rate period may not be observed at all except for very high initial moisture contents; in others constant rate drying continues to very low values of moisture content.
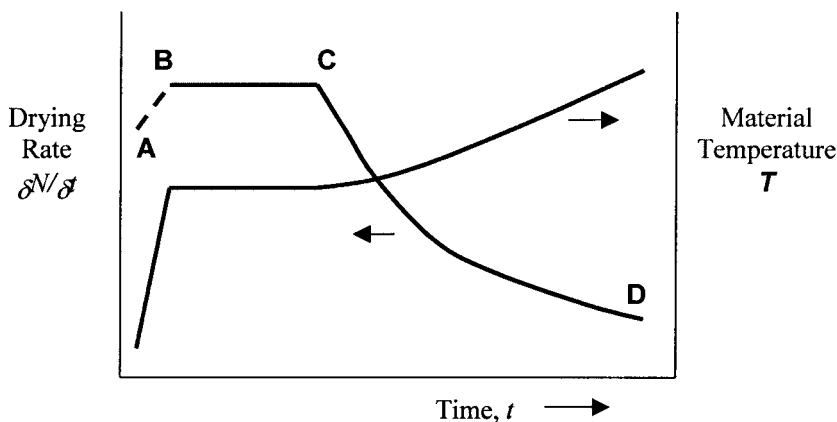

Fig. 5. The periods of drying.

2.3. Moisture equilibrium

In an evaporative drying operation, in order to leave the solid the liquid must be heated either to a temperature exceeding the saturation temperature of the liquid at the system pressure (in the case of a pure vapour atmosphere) or to a temperature at which its vapour pressure exceeds the partial pressure of the vapour in the surrounding medium (in the case of gas–vapour mixtures).

Moisture associated with a solid may be freely attached, or bound so that it does not exert its full vapour pressure. Materials whose structure retains bound moisture are known as hygroscopic materials, and biomass materials are generally of this type. For non-hygroscopic materials, drying will proceed provided the liquid vapour pressure is below either the saturation pressure of the surrounding atmosphere (for pure vapour) or the saturated vapour pressure (for a gas–vapour mixture)—if these conditions are met such materials could be completely dried. In the case of hygroscopic materials, however, as the moisture content falls the exerted vapour pressure falls, and an equilibrium moisture content is eventually reached for a given set of drying conditions at which the ratio of the actual to full vapour pressure (the activity) equals either the relative humidity of the drying medium (for gas–vapour mixtures) or the ratio of actual to saturation pressure (for pure vapour). Importantly, the equilibrium moisture content increases significantly as relative humidity increases (or degree of superheat falls), and if low final moistures are to be achieved then the transport medium must leave the drying chamber at well below 100% relative humidity (or with substantial superheat).

For hygroscopic materials, the equilibrium moisture content at ambient air conditions will represent the minimum moisture content the material can attain if being dried with ambient air. An important consequence of this is that if material dried to below its ambient air equilibrium moisture content is then stored for a significant period in ambient air, its moisture content will rise to the equilibrium value. In the case of woody biomass in a European country this might vary between 15 and 25% w/b depending on season and location [16].

2.4. Material temperature

The temperature history of the material as it undergoes drying also shows characteristic stages corresponding to the three drying periods defined in Section 2.2 (Fig. 5). Actual temperatures depend also on the drying medium and the heat transfer processes involved.

For gas–vapour mixtures during the constant rate period, the evaporating surface of the material will be at the wet bulb temperature of the drying medium for purely convective processes (approximately equal to the adiabatic saturation temperature for air/water mixtures), and provided no heat is lost this temperature will remain constant throughout the period. Where heat transfer is purely by conduction, the material surface temperature will remain at the liquid boiling point. Most real conductive process are at least partially convective, and here the

surface will lie between the wet bulb and boiling point temperatures. For pure vapour drying media during the constant rate period, the material surface temperature will remain at the liquid boiling point for both convective and conductive processes.

During the falling rate period, material surface temperature will be somewhere between the constant rate temperature and the actual or dry-bulb temperature of the drying medium. The temperature will rise as drying progresses.

2.5. Thermal efficiency of dryers

The thermal efficiency of a dryer is generally taken to be the ratio of the theoretical heat required to evaporate the moisture during drying (i.e. raise its temperature to the evaporation temperature and supply the latent heat of evaporation) divided by the net heat supplied to the dryer (i.e. the total heat supplied to the dryer from external sources less any heat recovered from the process for external use) [15]. Besides the heat required to evaporate the moisture, the total heat consumption of the dryer will include the heat necessary to raise the temperature of the solids and retained moisture, the heat in the humid exhaust leaving the dryer, and the heat losses from the dryer structure to the surrounding air. The first of these is unavoidable; the second and third may be influenced by dryer design and operation. The theoretical energy consumption for evaporation, assuming an ambient temperature of 15°C, lies in the range 2.48 to 2.57 GJ/tonne of water evaporated, depending on the wet bulb temperature [7].

3. Dryer classification

Many different classifications of dryers have been developed in attempts to rationalise what is a complex diversity of technologies, and simplify the process of dryer selection. Most classifications begin with major criteria which are usually either aspects of the drying process, usually mode of operation (batch or continuous) and mode of feed heating (conductive, convective or other), or the form of the feed (e.g. particle, sheet, block, paste, etc.), or both. There may then be further minor criteria such as gas flow pattern, solids transport method or type of drying medium employed before actual dryer types are given. Terminology can often be confusing—for example, conductive and convective dryers are also known as indirect and direct dryers, respectively.

Kemp and Bahu [17] have developed a detailed classification system based on three major and five minor criteria:

1. Mode of operation
    1.1. Batch (including semi-batch operation of 'continuous' dryers),
    1.2. Continuous (including semi-continuous operation).

2. Form of feed and product

2.1. Particles (including granules, agglomerates, pellets),
2.2. Film or sheet,
2.3. Block, slab or artefact,
2.4. Paste, slurry or solution.

3. Mode of heating
   3.1. Conduction or contact drying,
   3.2. Cross-circulated, through-circulated or dispersion convective drying,
   3.3. Radiation; infra-red, solar or flame radiation,
   3.4. Dielectric; radio-frequency or microwave radiation,
   3.5. Combinations; e.g. conductive/convective, radio-frequency enhancement.

4. Operating pressure—vacuum or atmospheric.
5. Gas flow pattern—none, cross-flow, co-current, counter-current, complex.
6. Solids flow pattern—stationary, well mixed, plug flow, complex.
7. Solids transport method—stationary, mechanical, airborne, combined.
8. Solids mixing—undisturbed layer, mechanical agitation, rotary, airborne.

The authors give classifications of the principal types of batch and continuous dryers using mode of heating as the primary criterion, and these are reproduced as Figs. 6 and 7.

It is not the purpose here to give descriptions of each of the multiplicity of dryer types contained in these classifications; the reader is referred instead to the extensive literature on the subject [10,15,11]. It should be understood, however, that the categories of Figs. 7 and 8 are by no means all-encompassing and there are numerous hybrid or intermediate types as well as sub-types within categories.

Perry [10] gives a more comprehensive and for our purposes more useful classification based on material to be dried, and this is reproduced with a few
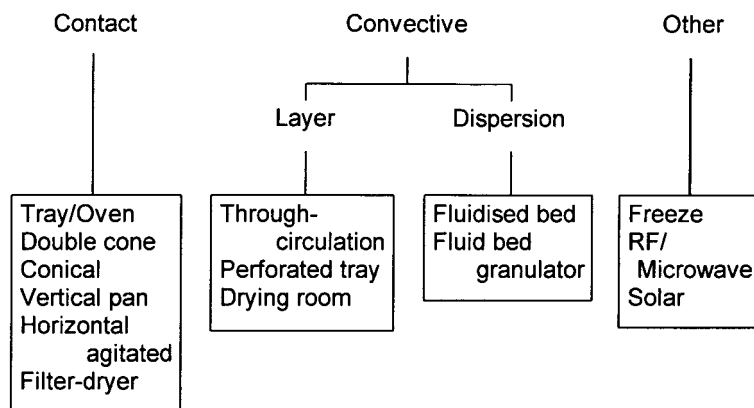

Fig. 6. Classification of batch dryers by heat transfer mode [17].

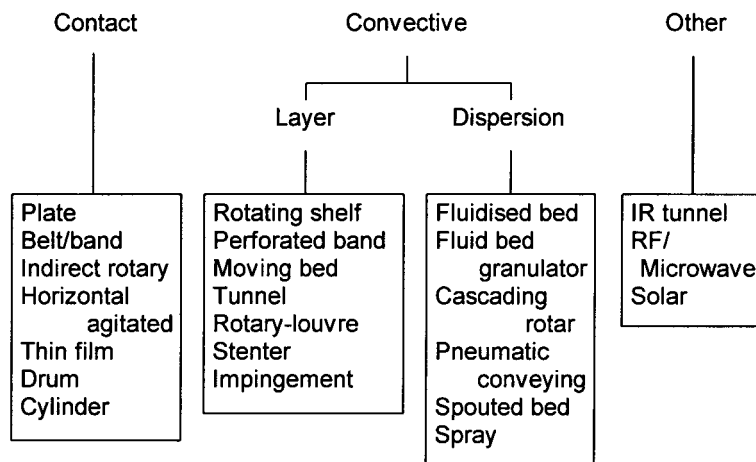| Contact	Convective		Other
	Layer	Dispersion	

Plate
Belt/band
Indirect rotary
Horizontal
  agitated
Thin film
Drum
Cylinder
	Rotating shelf
	Perforated band
	Moving bed
	Tunnel
	Rotary-louvre
	Stenter
	Impingement
		Fluidised bed
		Fluid bed
		  granulator
		Cascading
		  rotar
		Pneumatic
		  conveying
		Spouted bed
		Spray
			IR tunnel
			RF/
			  Microwave
			Solar

Fig. 7. Classification of continuous dryers by heat transfer mode [17].

modifications as Table 1. As the table clearly shows, many dryer types are highly specialised towards the type of material being dried.

When materials as different and milk and lumber require drying, this is not surprising. In the present review, the interest is in dryers of loose particular solids which, in the context of Table 1, are covered by the material type 'granular, crystalline or fibrous solids'. This can form a starting point for the more focused selection and description of dryer types suitable for an IGBP.

4. Drying in an integrated gasification bio-energy plant

4.1. Biomass properties relevant to drying

Biomass as a feedstock for an IGBP has a number of characteristics which place constraints on the selection of drying technology. These include size, density and friability, moisture properties, the effects of temperature with regard to emissions and fire risk, and the tolerance to different gaseous environments.

4.1.1. Physical characteristics

Biomass as a feedstock for an IGBP will be in the form of loose particulate solids of a fibrous nature. The biomass could either be in whole form in the case of, for example, olive pits or almond shells, or in comminuted form (chipped or chopped) as in the case of woody or herbaceous crops.

Size requirements are dictated largely by the gasification process, with each specific gasifier design having its own particle size range requirement. A throated downdraft gasifier will require particles of 20 to 80 mm, whereas an updraft gasifier can accept 10 to 200 mm and a fluid bed design generally requires

Table 1
Dryer classification based on material to be dried [10]

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when dry, dusty when wet, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, salt crystals, sand, ores, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Vacuum freeze Indirect type, batch or continuous operation	Heat-sensitive, readily oxidised materials. Usually only pharmaceuticals e.g. penicillin, blood plasma. Expensive	See under liquids	See under liquids	See under liquids	Usually only pharmaceuticals (fine chemicals) and related products which cannot be dried by other means. Expensive	See under granular solids	Special cases e.g. emulsion-coated films	See under granular solids
Pan Indirect type, batch operation	Atmospheric or vacuum. Small batches. Easily cleaned. Solvent recovery possible. Material agitated while dried	See under liquids	See under liquids	See under liquids	Small batches. Easily cleaned. Material agitated during drying, causing some degradation	Not applicable	Not applicable	Not applicable

Table 1 (*continued*)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when dry, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, salt crystals, sand, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, salt brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Vacuum rotary Indirect type, batch operation	Not applicable, except when pumping slowly on dry 'heel'	Only special cases, when pumping on dry 'heel'	Questionable. Material cakes to dryer wall and agitator. Solvents can be recovered	Non-sticking materials. Useful for large batches of heat-sensitive materials, solvent recovery	Useful for large batches of heat-sensitive materials, solvent recovery. Product will suffer grinding. Some dust generated	Not applicable	Not applicable	Not applicable
Screw conveyor and indirect rotary Indirect type, continuous operation	Applicable with dry product recirculation	Applicable with dry product recirculation	Generally requires dry product recirculation. Some dust generated	Low dust loss. Most materials and capacities, particularly those requiring steam temperatures	Low dust loss. Material must not stick or be temperature-sensitive	Not applicable	Not applicable	Not applicable

Table 1 (continued)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when wet, dusty when dry, e.g. centrifuged precipitates, pigments, clay, cement	>100 mesh, e.g. rayon staple, salt crystals, sand, ores, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, salt brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Fluid bed								
Batch, continuous, direct and indirect	Only with inert bed or dry-solids recirculator	See under liquids	See under liquids	Suitable if not too dusty	Generally crystals, granules and short fibres	Not applicable	Hot inert particles used for contacting	Hot inert particles used for contacting
Vibrating tray								
Indirect type, continuous operation	Not applicable	Not applicable	Not applicable	Free-flowing materials	Free-flowing materials that can be conveyed on a vibrating tray	Not applicable	Not applicable	Not applicable
Drum								
Indirect type, continuous operation	Single, double, twin. Atmospheric or vacuum. Product used flaky, usually dusty. High maintenance	See under liquids. Twin drums widely used	Only if paste/sludge can flow. See under liquids	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Cylinder								
Indirect type, continuous operation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Thin or mechanically weak sheets, dried in contact with heated surface. Surface effects obtainable	Materials not needing flat drying, tolerant of contact with hot drum

Table 1 (*continued*)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
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Infra-red Batch or continuous operation	Only thin films	Only thin films	Only thin layers	Only thin layers	Mainly for surface moisture. Not thick layers	Drying and baking paint and enamels	Usually combined with other methods. Useful if space limitations	Laboratory work, or combined with other methods
Dielectric Batch or continuous operation	Very expensive	Very expensive	Very expensive	Very expensive	Very expensive	Rapid drying of large objects	Final stages of paper drying	Foam rubber only
Tray and compartment Direct type, batch operation	Not applicable	Very small batch production. Laboratory drying	Suited to batch operation. Expensive at large capacities. Long drying times	See under pastes and sludges. Dust may be problem	See under pastes and sludges	See under pastes and sludges	Not applicable	See under pastes and sludges

Table 1 (continued)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
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Batch through-circulation Direct type, batch operation	Not applicable	Not applicable	Only if material preformed. Suited to batch operation. Shorter drying times than trays	Not applicable	Usually ≥30 mesh. Suited to smaller capacities (except large-capacity drying floors for agricultural products)	Primarily small objects	Not applicable	Not applicable
Tunnel, continuous tray Direct type, continuous operation	Not applicable	Not applicable	Small and large scale throughput	See under pastes and sludges. Vertical turbo applicable	Large-scale semi-continuous tray drying	Wide variety shapes and forms. Can be made continuous. Much used	Not applicable	Leather, wallboard, veneer

Table 1 (continued)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when dry, dusty when wet, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, rayon crystals, sand, ores, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, salt brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Continuous through-circulation								
Direct type, continuous operation	Not applicable	Only crystal filter dryer	Only if material preformed. Large capacities possible. Rotary louvre requires dry product recirculation	Generally not applicable, except rotary louvre in special cases	Generally ≥30 mesh. With rotary louvre, material tumbles, higher temperatures used	Smaller objects that can be stacked or piled. Rotary louvre not suited	Not applicable	Special designs required. Veneers. Rotary louvre not applicable
Direct rotary								
Direct type, continuous operation	Only with dry-product recirculation	See under liquids	Only non-sticking, non-dusting product. Recirculation may be necessary	Most materials and capacities, if dusting not excessive	Most materials and capacities, if dusting or crystal abrasion not excessive	Not applicable	Not applicable	Not applicable
Pneumatic conveying								

Table 1 (continued)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when wet, dusty when dry, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, crystals, sand, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, salt brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Direct type, continuous operation	Only if product recirculated to permit handling	See under liquids	Recirculation usually necessary to make suitable feed. Suited to high capacities. Disintegration usually required	Materials which are easily suspended in gas stream, lose moisture readily. Suited to high capacities	Materials which are easily suspended in gas stream, lose moisture readily. Suited to high capacities. Material may degrade	Not applicable	Not applicable	Not applicable
Spray Direct type, continuous operation	Suited to large capacities. Product usually powdery, spherical, free-flowing. High temperatures can be used with heat-sensitive materials	See under liquids. Pressure nozzle atomisers subject to erosion	Requires special pumping equipment to feed atomiser. See under liquids	Not applicable		Not applicable	Not applicable	Not applicable

Table 1 (*continued*)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when wet, dusty when dry, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, salt brick, rayon crystals, sand, ores, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Moving bed (gravity) Direct type, continuous operation	Not applicable	Not applicable	Not applicable	Not applicable	Material must be coarse granular and free-flowing, e.g. grain	Not applicable	Not applicable	Not applicable
Continuous sheeting Direct type, continuous operation					Not applicable	Not applicable	Different types for different applications. Suitable for non-contact with hot surfaces	Not applicable
Vacuum shelf								

Table 1 (*continued*)

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions, e.g. inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex	Pumpable suspensions, e.g. pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates	e.g. filter-press cakes, sedimentation sludges, centrifuged solids, starch	≤ 100 mesh, relatively free-flowing when dry, e.g. centrifuged precipitates, pigments, clay, cement	> 100 mesh, e.g. rayon staple, salt crystals, sand, ores, synthetic rubber, potato strips, wood chips, rice hulls, beans, grain	e.g. pottery, salt brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber	e.g. paper, impregnated fabrics, cloth, cellophane, plastic sheets	e.g. veneer, wallboard, photograph prints, leather, foam rubber sheets
Indirect type, batch operation	Not applicable	Applicable for small batch production	Suited to batch operation, small capacities, heat-sensitive or easily oxidised materials. Solvent recovery possible	See under pastes and sludges	See under pastes and sludges	See under pastes and sludges	Not applicable	See under pastes and sludges

Fig. 8. Wood chip size distributions [16].

particles of < 10 mm [18]. Fluid bed gasifiers are able to accept very small particles; however pre-treatment costs can escalate rapidly if the biomass has to be comminuted and mean particle sizes below those attainable from chippers are required (∼5 mm [3]). Example size distributions from wood knife chipper are shown in Fig. 8. If comminution is necessary, the size range can usually be controlled within certain limits at the comminution stage without greatly affecting comminution costs, in order to meet specific gasifier, dryer or handling requirements. It is assumed here that fines will normally be screened out prior to the drying process.

In most cases, the material will have a bulk density in the range 50 to 300 kg m^{-3}, depending on type and moisture content. Usually the bulk material will have only moderate flow properties, but will readily permit through-circulation of the drying medium. The particulate solids are generally not friable under all but the most strongly agitated of processes, and physical damage or generation of significant amounts of additional dust within the drying process is therefore not normally a problem.

4.1.2. Moisture properties

Typical moisture content of biomass feedstocks as received at a bio-energy plant and as required by the gasification process has been discussed in Section 1.1. Biomass materials of this type are hygroscopic (see Section 2.2). Equilibrium moisture content can vary from 25% w/b or more if the drying medium is close to saturation, down to below 1% w/b where the medium is exceptionally dry [16]. As indicated in Section 2.3, under ambient air conditions typical of European locations the equilibrium moisture content of woody biomass will range approximately from 25 to 15% w/b. Clearly if very low moisture contents are

required, there are major consequences for the drying medium requirement and post-dryer handling.

For most agricultural materials the constant rate period during drying is either very short or non-existent [19] (see Section 2.1); falling rate drying commences immediately after the short heating period, which is often ignored in analysis or modelling. In tests on various different types of wood chip carried out by Nellist [1], no constant rate was observed when drying from up to 60% w/b.

4.1.3. Emissions

The subject of emissions from the drying of biomass materials has recently been reviewed [20]. Biomass materials of this type have a very high volatile content. Emissions arise either from vaporization of volatile components in the biomass, or from thermal degradation of the biomass. Vaporised components can be further subdivided into those that remain volatile at ambient conditions, and those that condense. The most volatile vaporised components consist of monoterpenes, which are emitted naturally at ambient temperatures but whose emission rate increases with temperature, particularly above 100°C. They are strong-smelling irritants whose presence becomes annoying in the long run. The haze visible above a forest on a warm day is due to photochemical reactions involving these species.

Condensable components create more of a problem, being principally responsible for so-called 'blue haze', a more localised discoloration of the exhaust plume. The visual nuisance caused by blue haze has to date been the source of greatest concern regarding emissions from dryers, although the phenomenon can also cause odour problems. These condensable components tend to be released at material temperatures of greater than 100°C. Thermal degradation products are released at higher wood temperatures still (>200°C for short drying times, rather less for longer drying times), and the rate of loss accelerates rapidly as temperature is increased further.

The release of all these components would ideally occur in the gasifier, and any premature release represents a loss of potentially gasifiable material and is therefore to be minimised. It may also require the provision of clean-up equipment for exhaust gas or condensate streams, as may the excessive release of solid particulate material into the atmosphere. Solid particulates may usually be dealt with satisfactorily with cyclones or bag filters. Blue haze however is composed largely of sub-micron aerosols, and these are notoriously difficult to remove with conventional gas cleaning techniques such as wet scrubbers, requiring instead more exotic and expensive methods such as wet electrostatic precipitation or electro-filter beds [20]. As a general rule, therefore, material temperatures should be kept below 100°C for all processes where possible, although material temperatures up to ~150°C are probably acceptable for shorter residence time processes (<1 h). The ability of biomass materials to tolerate temperatures up to these limits with no serious consequences means that drying options specifically designed for heat-sensitive materials, such as vacuum methods, are unnecessary.

The actual emissions (gaseous and particulate) to be expected from a given biomass drying installation depend on a range of factors, and cannot be easily

predicted. Many of the factors are in the control of the operator or process designer. Factors may be grouped into three categories:

4.1.3.1. Dryer type. Different dryers have widely differing characteristics regarding emissions; these are discussed in Section 5 for the different dryer types. However, key design features of relevance include:

- whether the system is closed or open—i.e. whether the drying medium is reused, or whether it is exhausted at atmosphere;
- the degree to which material is agitated and broken up in the drying process;
- the residence time of material in the dryer;
- whether any emissions abatement equipment is supplied with the dryer.

4.1.3.2. Drying medium characteristics. Important factors include the temperature of the drying medium, and the velocity of the medium through the dryer. As indicated above, low drying medium temperatures which keep the material temperature below $100°C$ will not cause pre-pyrolysis and thus will minimise any blue haze problems. Fixed bed dryers (see Section 5.1) will minimise this problem from the use of low temperature heat.

High gas velocities will tend to entrain fine particles and some entrainment will always occur. This is however, much easier to handle with physical filtration equipment. Fixed bed dryers (Section 5.1) will minimise this problem from the very low superficial gas velocity.

Steam dryers (see Sections 5.5.1 and 5.6.1), although having no gaseous emissions, pose a special problem of producing a contaminated waste water which requires conventional water treatment as the chemical oxygen demand will tend to be high. There is so little data or experience with such systems that estimation of cost or performance is not possible.

4.1.3.3. Feedstock characteristics. Emissions vary very much according to the type of biomass being dried. Even different types of wood can exhibit very different emissions characteristics, including the species evolved and the temperature at which they evolve. Also, feedstock size range is very important; a wide size range may result in the smaller particles being over-dried, leading to excessive thermal degradation, as well as a propensity to be entrained in the exiting gas flow.

The requirement to implement emissions reduction measures at a particular drying installation will depend also on the immediate location of the installation (i.e. is it close to a residential area), and on the local legislative limits applying. These cannot be generalised as they will vary from country to country and sometimes from region to region. Furthermore regulations governing certain emissions of more recent concern, such as volatile organic compounds (VOCs), are still evolving, and compliance is a matter of hitting a moving target.

4.1.4. Fire or explosion risk

A dryer fire or explosion can arise from two causes—ignition of a dust cloud brought about by the presence of a large proportion of fines in the material, and ignition of the combustible gaseous emissions from the drying material. It has been assumed that fines will normally be screened out prior to the dryer; however in certain special cases this may be undesirable (see Section 5.3, for example). If significant quantities of fines are present, not only is there a risk of dust ignition, but the release of the combustible products of thermal degradation which occurs inevitably to the over-drying of fines may increase to dangerous levels.

Both causes of ignition require the presence of sufficient oxygen and a sufficiently high temperature. Under conditions found in most dryers, the risk of fire or explosion from flammable vapours becomes significant if the drying medium has an O_2 concentration of $\sim$10% by volume or more [21]. Under these circumstances high drying medium inlet temperatures should be avoided, both to minimise volatile emissions and to reduce the possibility of ignition. Actual ignition temperature is a function of local gaseous compositions and is difficult to predict, but problems have been encountered with wood chips in rotary dryers using combustion products with a temporarily high oxygen concentration at inlet temperatures of well below 300°C [22]. A probable safe working limit is in the region of 250°C. In those cases where combustion products with an oxygen content well below 10% are used as the drying medium, much higher inlet temperatures may be used; one rotary dryer manufacturer quotes up to 1000°C for very wet materials in co-current operation [23]. If high temperatures are used, however, it becomes very important both to minimise the possibility of air in-leakage and to ensure that material temperatures do not exceed the limits discussed in Section 4.1.3.

4.1.5. Tolerance to different gaseous environments

For the three dying media likely to be available for use in an IGBP, namely air, steam and combustion products, the only issue of feedstock material compatibility is that of the O_2 concentration in the context of fire or explosion risk as discussed in the previous section. Otherwise, from the point of view of adverse effects on the feedstock material all three are equally suitable.

4.2. Plant characteristics relevant to drying

The plant also has a number of characteristics which influence the choice of dryer. These include the available heat sources, the mode of operation of the plant and its capacity range.

4.2.1. Sources of heat

The requirement to integrate the drying process into the overall plant by making use of sources of thermal energy available at other points in the plant has already been stated (Section 1.2). This implies that the selected dryer must either be of the conductive or convective type, or a combination of the two. For an

IGBP for power or CHP, suitable sources of heat may take the following forms (Fig. 9):

- hot fuel gas which requires cooling (via heat exchange with secondary medium);
- hot combustion products from the engine or turbine (direct or via heat exchange with secondary medium);
- hot products from combustion at the dryer of diverted biomass or fuel gas;
- hot air from air cooler in a steam or combined cycle plant (direct or via heat exchange with secondary medium);
- hot water from engine cooling and/or condenser in a steam or combined cycle plant (via heat exchange with secondary medium).

The secondary medium will in almost all cases be either air or steam. In the case of CHP plants in which steam is being raised for external use, drying may be a competing demand and a techno-economic optimisation may become necessary.

4.2.2. Mode of operation

The bio-energy plant, whether for power or CHP, will be required to run continuously for extended periods. In order to make most efficient use of the heat sources which will therefore be continuously available, the drying technology should also be of the continuous type. However, continuous dryers tend to be more expensive capital items than batch dryers which usually involve relatively simple technology, although this can in turn be offset by the greater operational costs associated with batch systems because of handling requirements. These economic considerations may under certain circumstances outweigh issues of overall thermal efficiency, and batch methods should therefore be considered at

Fig. 9. Sources of drying heat in an IGBP.

very small plant scales where the cost of continuous methods may become excessive, and where the method permits large batch sizes and long drying times so that the ratio of loading/unloading to drying time (i.e. the period during which the available process heat is not being used) can be minimised.

4.2.3. Capacity range

An IGBP for power or CHP may have a thermal capacity ranging from 100 kW_{th} at the smallest farm scale to maybe 100 MW_e for the largest envisaged power generation plants that could be competitive with coal and gas [24]. This corresponds to a range in dry throughput of biomass of less than 20 kg/h to over 50 tonnes/h. This is a very wide range, and most available drying technologies will be suited to some part of it at least in terms of capacity. At the larger scales, of course, it will be reasonable to consider multiple units. It is therefore only possible to rule out drying technologies at the very smallest end of the capacity range on these grounds alone—those designed for laboratory work, for example.

5. Suitable technologies for an integrated gasification bio-energy plant

An initial selection of dryer technologies may be made using the classification given in Table 1. As was pointed out in Section 3, the material category corresponding to IGBP feedstocks is 'granular, crystalline or fibrous solids'. Small batch technologies, vacuum technologies, those technologies requiring good free-flow characteristics and those technologies not based on conductive or convective heat transfer may be eliminated, for the reasons given in Sections 4.1 and 4.2. Tunnel or cross-flow tray types may be eliminated, as these would always be rejected in favour of through-flow systems if the latter are applicable (as is the case here), due to their superior heat and mass transfer rates. Also, certain specialised types may be rejected, such as screw conveyor dryers which are rarely used except when the material has to be conveyed over large distances. The following categories then remain:

- batch through-circulation;
- continuous through-circulation;
- direct rotary;
- indirect rotary;
- fluid bed;
- pneumatic conveying.

Each of these categories of dryer is therefore broadly suitable for IGBP feedstocks. In some cases however the categories are quite general and contain a variety of design concepts, only some of which may be appropriate.

Dryer types which might be suited to IGBP feedstocks will fall generally into three groups:

- dryers that have been designed specifically for IGBP feedstocks;

- dryers that have been specifically designed for another material but are deemed to be well suited to **IGBP** feedstocks (possibly with some adaptation);
- less specialised dryers that can accept a range of material types, but which would be suitable for **IGBP** feedstocks.

In the case of specialised dryer designs, there may in some cases by only a single manufacturer or a very limited number. On the other hand for the less specialised design concepts there may be a multitude of manufacturers each with their own range of subtly different models.

Sections 5.1–5.6 will focus on each of the identified dryer categories, defining the main sub-groupings where appropriate and giving detailed descriptions of those types falling into the three groups referred to above.

5.1. Batch through-circulation

Through-circulation methods are attractive because of the efficient heat and mass transfer involved, and because of the minimal disturbance of the material being dried. In most industrial contexts, batch through-circulation drying implies tray dryers, where the material is placed on a number of trays, usually stacked vertically in two or more columns and enclosed in a cabinet. A range of configurations is possible. The trays will have screen or perforated bases to allow through-circulation of the drying medium, usually air. As indicated in Table 1 these are relatively small-capacity devices, and in Section 4.2.2 reasons were given why small-capacity batch methods were inappropriate for **IGBP** feedstocks.

One group of drying techniques which can be classed as batch through-circulation methods do however provide an option for IGBP feedstocks, because of their low capital cost, high capacities, and particularly their characteristic of low intensity drying which makes them well suited to the use of low grade heat. These are the fixed-bed perforated floor methods used widely in the agricultural industry, particularly for drying grain [21].

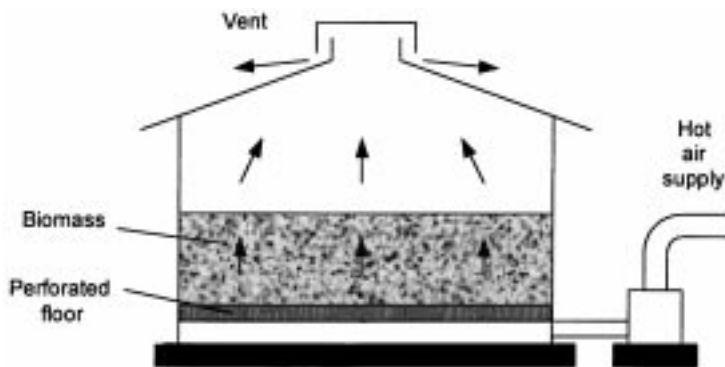The conventional form of system comprises a containing bin or silo (Fig. 10) or

Fig. 10. Perforated floor bin dryer.

simply a room, with a perforated floor through which the hot drying medium, usually air but possibly combustion products, can be made to flow via a plenum by the use of electrically powered fans. The wet material is loaded onto the perforated floor to form a bed, the depth being chosen to give the desired drying characteristics. Drying then takes place, the batch time being anywhere from a few hours to a number of days. At the completion of this period the dried material is removed and deposited in a buffer store and a fresh batch of wet material loaded. Means of heating the drying medium (if required) may be provided at inlet, either electrically or by heat exchange from a secondary carrier such as steam or the combustion products of a smaller burner. Alternatively an already heated drying medium may be used directly. These are simple systems which would require little adaptation for IGBP feedstocks, although their performance characteristics would clearly be different to those when drying grain.

A more sophisticated design used in grain drying and of potential application to IGBP feedstocks is the top-drying bin (Fig. 11), in which the main perforated floor is located near the top of the bin and supports a relatively shallow bed of drying material [21]. Once dry, this material is allowed to fall through doors in the perforated floor into the lower, much larger region of the bin which acts as a store. The hot drying medium is admitted to this region above the maximum material level. In some designs, the base of this zone is also perforated and a flow of ambient air is circulated up through the stored dried material to augment the heated flow entering above (as shown in Fig. 11), thereby reclaiming some of the sensible heat in the dried material at the expense of some fan power. Again provision may be made for heating the primary drying medium if this is required.

With both conventional and top-drying systems it is possible to automate the material loading and unloading to varying degrees, greater degrees of automation requiring greater capital outlay particularly for large systems, although the poor
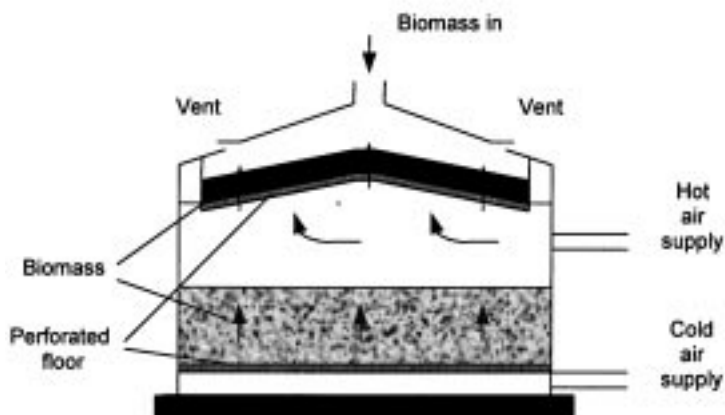

Fig. 11. Top drying bin.

flow properties of IGBP feedstocks compared with grain may limit the possibilities of direct read-across from grain systems.

To the author's knowledge no such dryers are marketed specifically for IGBP feedstocks. They are principally designed for grain, with some manufacturers offering adapted designs for other agricultural product such as peanuts or rice [25]. There are nevertheless cases where simple drying bins and drying floors designed for grain have been used for the drying of IGBP feedstocks in small bio-energy plants [26], in which any necessary adaptation has been carried out by the user. It is important however to bear in mind the large differences in bulk density referred to earlier, particularly for more sophisticated systems. Grain drying bins and drying floors may be purchased or designed and built by the user at a wide range of capacities. The use of multiple units at larger plant sizes may improve utilisation of handling equipment and fan power, and make better use of available heat.

The choice of depth of the fixed bed in such systems is a key consideration. Fixed-bed through-circulation heated drying of wood chips has been studied by Nellist at Silsoe Research Institute in the UK [1], where models have been developed and validated to describe the process. The issue of bed depth is addressed and recommendations are made. The main recommendation is for relatively shallow depths (0.4 to 0.6 m), as these minimise fan power requirements and reduce over-drying of the lower layers. However, the shallower the bed, the shorter the drying time to reach a target mean moisture and the greater the frequency of charging and discharging. Drying performance will also be influenced by drying medium humidity at inlet. If the direct use of relatively humid combustion products is being considered, it may be advantageous to exchange heat with relatively dry air and use the air instead.

A drawback with fixed bed through-circulation methods is that they invariably produce a large vertical gradient in moisture content of the dried bed. The lower levels of the bed almost always reach the inlet temperature of the drying medium, and this effectively limits the latter to the material temperature limit which for long residence time systems such as this would be 100°C or less (see Section 4.1.3). Importantly, the dried product needs to be thoroughly mixed, and possibly allowed to equilibrate for a period in a buffer store, before being used. If in the process the material is exposed to ambient conditions for any length of time, the moisture content may rise (see Section 2.3). In top-drying systems, mixing and equilibration is accomplished to some extent in the integral store [21].

In general, the characteristics of low gas velocity, low temperatures and a static bed associated with these methods mean that there is no need for clean-up of the gaseous exhaust. This adds further to their capital cost advantage.

5.2. Continuous through-circulation

Continuous through-circulation methods take one of two basic forms. By far the most widely used is the band or belt dryer, in which the drying medium is blown through a thin static layer of material on a moving band. Less common is

the rotary louvre dryer, in which material passes along a slowly rotating tube, forming a rolling bed through which drying medium is blown from an outer annulus via louvres. Continuous through-circulation dryers are most often used for materials that require gentle handling.

5.2.1. Band dryers

The band dryer operates by blowing the hot drying medium vertically through a thin layer of material carried on a permeable band which moves horizontally through the enclosed drying chamber. Gas flow may be upward or downward. In the single-stage single-pass design (Fig. 12), a continuous band runs the whole length of the dryer. In the multi-stage single-pass design (Fig. 13), a number of bands are arranged in series, with the material discharged from the end of one band onto the beginning of the next and in the process exposing new surfaces to the drying medium. In the multi-pass design, a number of bands are installed one above the other, each discharging onto the band below (Fig. 14). The same re-exposure benefit is gained, but dryer length is much reduced at the expense of height.

The drying medium is usually either air or combustion products or a mixture of both, and is moved through the dryer by a number of fans. In most modern systems, the dryer is divided up into zones (usually corresponding to the stages in a multi-stage dryer) through which the drying medium progressively passes (as in Figs. 12 and 13). Each zone usually has its own fan. In the case of ambient inlet air systems each zone will have either a steam heater or a gas or oil burner for heating and re-heating of the air. The fans and heaters are often located in a side
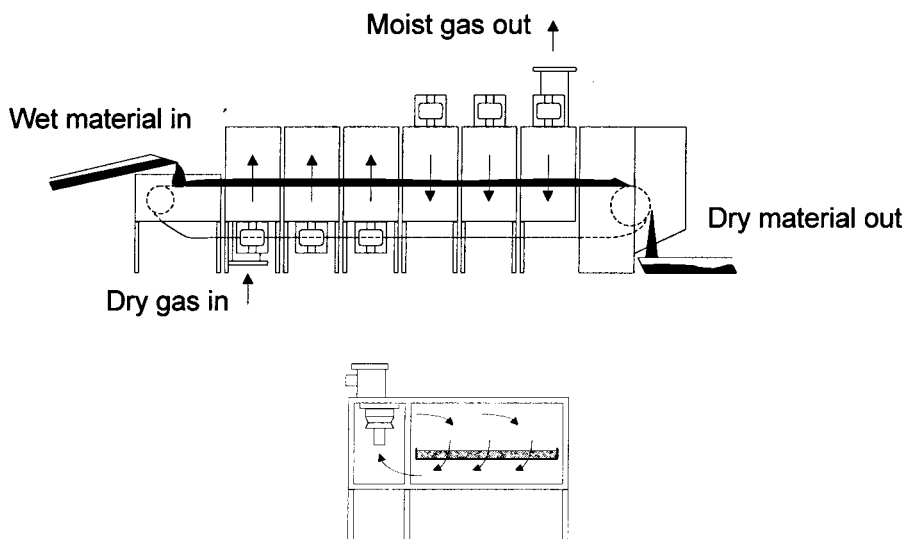

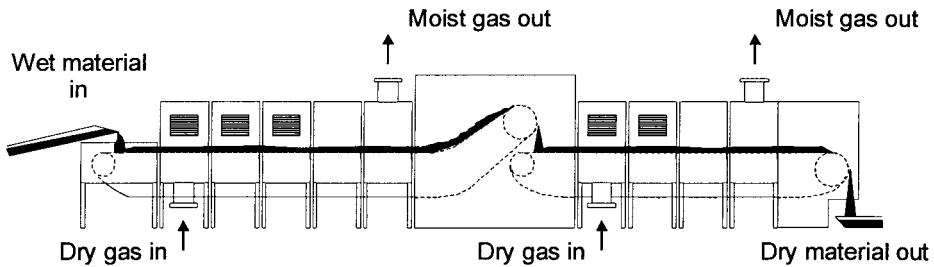Fig. 12. Single stage single pass band dryer.

Fig. 13. Multi-stage single pass band dryer.

compartment, as shown in Fig. 12. In the case of systems using pre-heated air or hot combustion products as the drying medium, there may be ports in each zone for the progressive admixture of fresh gas. The general movement from drying medium inlet to outlet can be either co- or counter-current with respect to the passage of material.

Even spreading of the material over the band at the material inlet and between each stage or pass is very important, and considerable attention is paid to this aspect by designers resulting in many patented designs. In some cases these are material-specific, with at least one commercially available system (made by Saxlund of Norway) having been designed specifically for wood fuel chips [27].

The band dryer has the advantage that both residence time and, in most designs, temperature can be closely controlled. This is of particular use in drying heat-sensitive materials. Residence time for a given band length is set simply by the speed of the band. Temperature control is achieved either by controlling the steam flow to each steam heater or the fuel flow to each burner, or in hot gas systems where progressive admixture is possible, controlling the flow rate to each hot gas port. Temperature is however limited to around 350°C because of the problems of lubricating the conveyor, chain and roller drives [10]. Because of the relatively shallow depth of material on the band (usually in the range 2 to 15 cm) the uniformity of drying is very good. On multi-stage and multi-pass designs, bed depth can be varied through the dryer if desired by adopting different band
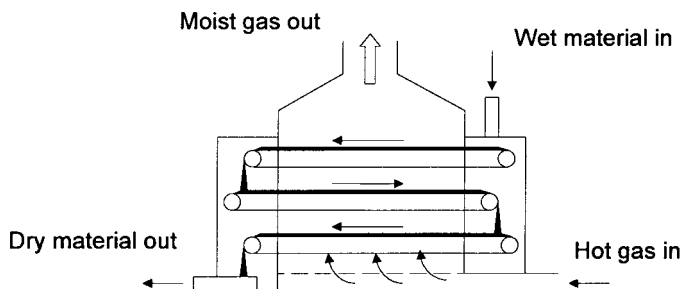

Fig. 14. Multi-stage multi-pass band dryer.

speeds. Because the material suffers very little agitation during the drying process (particularly for single pass designs), band dryers are particularly well suited to friable materials, although as pointed out in Section 4.1.1 this would not generally be of advantage to IGBP feedstocks.

Typical performance data for a steam-heated single-stage single-pass design drying wood chips at a throughput appropriate for a small plant of thermal input around 8 MW are given in Table 2.

Entrainment of fines with this type of dryer should be low due to the low velocities and static material bed. A bag filter may still however be necessary, depending on local regulations. A major advantage of using indirect steam re-heating of air in this context would be the much reduced volume flow of gaseous emissions, so that if clean-up equipment is required it is much smaller and therefore cheaper.

5.2.2. Rotary louvre dryers

The rotary louvre dryer (Fig. 15) may be thought of as a direct rotary dryer; however, unlike more conventional rotary dryers (Section 5.3) it uses through-circulation drying, and so is included in the present section. The dryer comprises a long tube inclined at a small angle to the horizontal which rotates slowly. On the inner side of the tube wall are a large number of longitudinal channels, each with a hinged tangential louvre covering it. The louvres overlap, forming an inner cylinder which carries the material being dried. The material forms a slumping bed moving slowly down the tube as it rotates. The drying medium is admitted along the channels and blows through the bed of material via the louvres, exiting at the material outlet. A stationary head plate constrains the drying medium to enter only those channels which are covered by material bed (Fig. 16).

The material depth tends to increase as the outlet is approached. The gas velocity through the bed is therefore at its lowest near the exit where the material is driest, and this tends to reduce entrainment. The depth is controlled by an exit weir over which the material passes to reach the dryer outlet. Drying is highly uniform as the material is constantly rolling in the bed; however, the particle motion is relatively gentle compared with cascading rotary techniques (see Section

Table 2
Performance data for band dryer (Wolverine Proctor Schwartz)

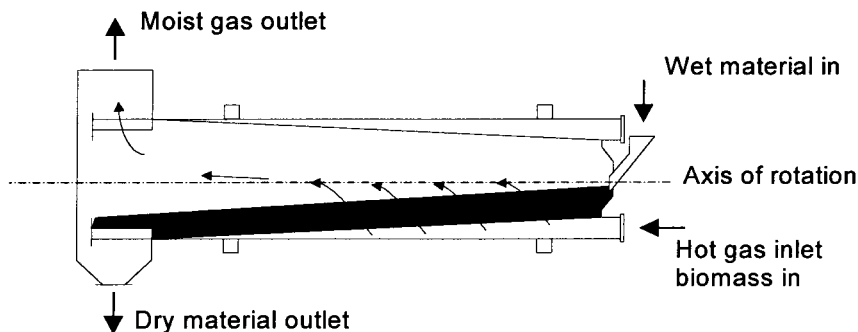|	
Biomass type	Wood chips
Biomass flow rate (dry)	0.42 kg/s
Biomass moisture content in	50% w/b
Biomass moisture content out	15% w/b
Steam flow rate	0.66 kg/s
Steam pressure (sat.)	2000 kPa
Air flow rate (dry)	0.54 kg/s
Dryer volume	88 m^3
Power consumption	60 kW
Capital cost ex works	£235,000

Fig. 15. Rotary louvre dryer.

5.3), and this also leads to low entrainment. Exhaust clean-up equipment is more likely to be required than with band dryers, however, if fines are present in significant quantities, as the material is agitated to some extent. Temperature along the dryer may be controlled if required by using multiple gas feeds of different temperatures along the dryer.

The drying medium is usually air or hot combustion products. Direct oil or gas burners or indirect steam heaters can be incorporated for the heating of ambient air prior to the drying section inlet. An upper temperature limit of 600°C has been quoted [10].

Heat transfer in the rotary louvre dryer is very efficient as with other through-circulation methods, and dryer volumes are substantially less than for an equivalent cascade rotary dryer (Section 5.3). However, this is offset by greater complexity of construction which pushes capital costs up. Pressure drop across the dryer is also higher, necessitating greater fan power. The dryer is best suited to
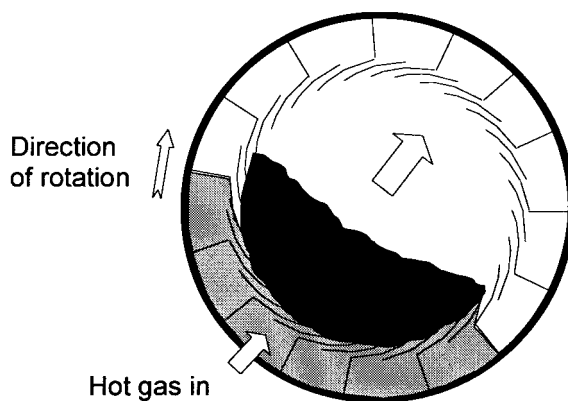

Fig. 16. Gas flow—rotary louvre dryer.

free-flowing materials for obvious reasons; the design is prone to clogging [11], and this could prove a problem with some IGBP feedstocks.

5.3. Direct rotary

The direct rotary dryer, or rotary cascade dryer, is very widely used in industry for a wide range of materials. It is often the dryer of choice on economical grounds where air or combustion products are the drying medium and the material can withstand moderate agitation. The rotary cascade is easily the most often encountered type in the limited number of existing large-scale IGBPs, as well as in large wood-chip combustion plant [28,29]. It is well-understood, empirical design rules exist, and the rotary cascade dryer is thus perceived as a low risk choice.

The dryer (Fig. 17) consists of a cylindrical shell, inclined at a small degree to the horizontal and rotating at between about 1 and 10 r.p.m. depending on size. The length to diameter ratio of the shell usually lies between 4 and 10, with actual diameter ranging from <1 m to >6 m depending on throughput. Material is loaded into the shell at the upper end, passes along the shell and exits at the lower end. The drying medium, either heated air or combustion products, may either enter at the upper end (parallel-flow arrangement) or at the lower end (counter-flow arrangement). On the inside of the shell are a number of longitudinal flights (Fig. 18) which may be continuous or staggered, and which are designed to lift the material around the periphery of the dryer and cascade it in a uniform curtain through the passing gases. The material thus moves down the dryer by a combination of gravity and, in the case of parallel-flow dryers, entrainment with the drying medium.

Residence time in the dryer is controlled by a number of factors including flight design (the amount of hold-up on the flight), number of flights, rotational speed, gas velocity, dryer length and dryer inclination. The overall hold-up bulk volume
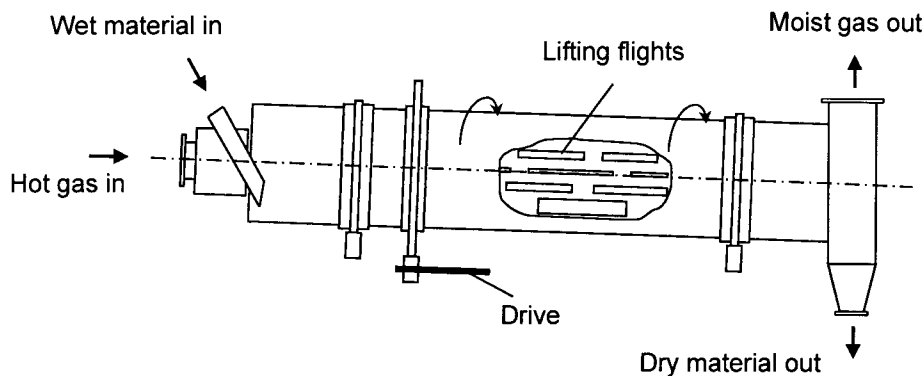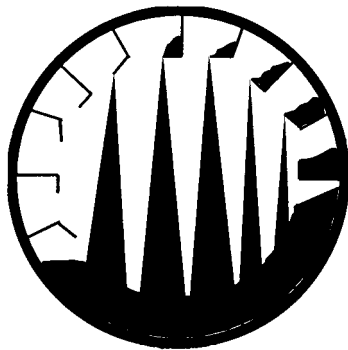

Fig. 17. Rotary cascade dryer.

Fig. 18. Typical flight arrangement, rotary cascade dryer.

is usually in the range 3 to 12% of dryer volume, 7 to 8% being a common figure [15]. Drying takes place almost totally during the period when the material is falling through the gas stream; drying whilst being lifted by the flights is minimal. In a well designed and operated dryer, there should be no significant bed of material in the base of the shell.

Overall heat transfer is less effective than for through-circulation systems, and higher inlet temperatures are generally used. Heat transfer is generally superior in counter-flow systems; however, in such systems the driest material sees the highest drying medium temperature, and they are generally therefore not suitable for temperature-limited materials including IGBP feedstocks. Inlet temperatures of up to 1000°C are possible with non-heat-sensitive materials, or with very wet materials in a parallel-flow configuration (as the drying medium loses temperature rapidly during the initial drying stages), although temperatures above about 600°C would require either expensive alloy steels or refractory lining [30]. However, in the interests of safety (see Section 4.1.4) inlet temperatures when drying wood chips in commercial installations have often been limited to about 250°C [22]. The dryer is usually operated under slight suction with an induced draught fan at the exit, and sealing problems leading to air in-leakage have been a weakness in many installations trying to maintain a low-oxygen environment.

Gas velocities are usually in the range of 0.5 to 5 ms^{-1} at exit, depending on type of material, flow arrangement and the amount of carry-over of material due to entrainment [10]. A design value of 2 to 3 ms^{-1} is typical in modern systems. The unavoidable carry-over of entrained material and the relatively large gas volume flow rates make sizeable dust removal equipment usually essential, and this can represent a significant additional capital cost. However, entrainment can also serve to reduce the residence time of the smaller particles and inhibit over-drying.

Exhaust gas recycle is often incorporated in direct rotary dryers to try to reduce the drying medium requirement and the exhaust gas flow rate. This results in more humid conditions in the dryer. Less drying can take place; however, overall

thermal efficiency may be improved. In general, thermal efficiency for direct rotary dryers lies in the range 50 to 75% [15], the highest values being found for counter-current systems with high inlet temperatures. A typical set of performance data for wood chips at a throughput corresponding to a plant thermal input of around 20 MW is given in Table 3.

Many systems are offered with heating equipment at inlet, often in the form of a gas burner. In at least one system for drying wood chips, fines separated in the exhaust cyclone are used to fire a small combustor to provide additional hot gases for the dryer [23]. In this case it would make sense not to separate out the fines prior to the dryer, although fire risk and blue haze emissions may be increased.

5.4. Indirect rotary

There are three main reasons for employing indirect (conductive) rather than direct (convective) heating in a rotary dryer:

- the material being dried cannot be exposed to combustion products;
- direct heating will lead to excessive entrainment and carry-over of fines or dust;
- a low-cost source of low to medium pressure steam is available.

Where the heating medium is combustion products but the material cannot be exposed directly to them, a number of designs exist for bringing the gases into indirect contact with the material, including single-pass concentric outer shells, or double-pass arrangements with an outer shell and an inner tube. As this situation does not arise with IGBP feedstocks, these designs will not be considered further.

It may well be the case, however, that a suitable source of steam may be available, and that benefits of much reduced exhaust gas flow and carry-over make an indirect rotary option attractive. In this case, the most usual form of dryer is known as a steam-tube rotary dryer (Fig. 19).

Steam tubes running the full length of the dryer are arranged in a number of concentric rows moving inwards from the dryer shell. The number of rows will depend on the nature of the feed; Fig. 19 shows two. The tubes are fixed to the dryer end plates and rotate with it. The dryer shell is usually inclined at a small

Table 3
Performance data for rotary cascade dryer (M.E.C. Company)

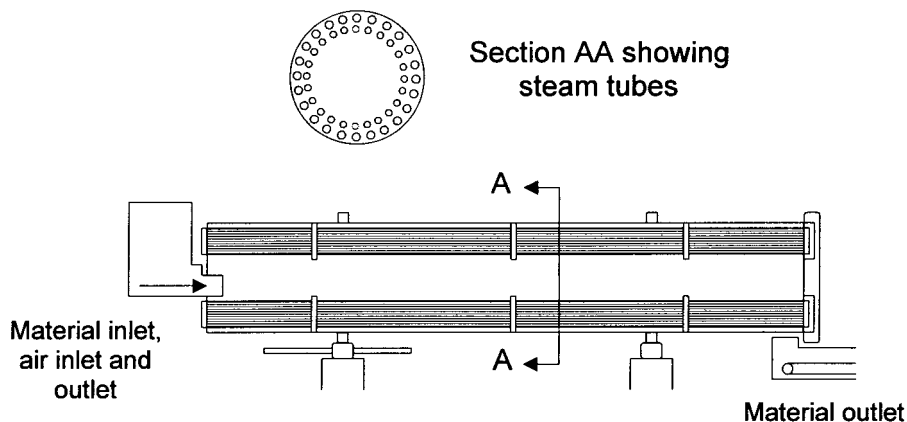|	
Biomass type	Wood chips
Biomass flow rate (dry)	0.97 kg/s
Biomass moisture content in	50% w/b
Biomass moisture content out	15% w/b
Drying medium type	Flue gas
Drying medium flow rate (dry)	12.4 kg/s
Drying medium temperature in	263°C
Dryer volume	135 m^3
Power consumption	112 kW
Capital cost ex works	£280,000

Fig. 19. Steam-tube rotary dryer.

angle to the horizontal, and the wet material enters the shell at one end and moves down the dryer by gravity, assisted by the ploughing effect as the tubes rotate through the material bed. Flights may be fitted to improve the motion. The arrangement gives excellent material contact with the conducting surfaces of the tubes. A small flow of air is employed, usually counter-current to the material flow, to effect the removal of the evaporated moisture—the volume flow is of course very low compared with direct designs. Hold-up within the dryer is usually controlled by a weir plate or similar device at the discharge end, as with the rotary louvre dryer (Section 5.2).

Heat transfer in these devices is by conduction from surfaces at or close to the steam temperature. The material temperature will normally be close to the moisture boiling point at discharge, rather hotter than in direct systems (see Section 2.4). Saturated steam is normally used, typically at 10 bar, and the steam passages will be designed to be fully condensing. Thermal efficiency can be very high, in the range 75 to 90% [15], although this takes no account of the efficiency of steam generation. Capital costs can also be high, however, due to the tubing requirements, rotating seals and so forth. This may be partially offset by the lower cost of back end clean-up due to the low exhaust gas flow volume. Typical performance data for wood chips at a throughput appropriate for a small plant of thermal input about 8 MW are given in Table 4.

5.5. Fluid bed

If the gas velocity through the bed of an up-flow through-circulation dryer is steadily increased, a point is reached where the bed becomes fluidised—that is, it behaves like a fluid. Between this point and that where the velocity is sufficient to entrain the typical particle and carry it out of the bed, lies the fluid or fluidised

Table 4
Performance data for steam tube rotary dryer (Mitchell Dryers Ltd)

Biomass type	Wood chips
Biomass flow rate (dry)	0.42 kg/s
Biomass moisture content in	50% w/b
Biomass moisture content out	15% w/b
Steam flow rate	0.44 kg/s
Steam pressure (sat.)	1100 kPa
Air flow rate (dry)	0.34 kg/s
Steam tube area	274 m^2
Power consumption	50 kW
Capital cost ex works	£380,000

bed regime. Once entrainment dominates, we enter the regime of pneumatic conveying dryers (Section 5.6).

Fluid beds are characterised by very high heat transfer rates and very good mixing; they represent in many respects ideal drying conditions [15]. In fluid bed dryers (Fig. 20) the fluidising gas is the drying medium, and may be air, combustion products or in special cases steam (see Section 5.5.1.). Usually the source of heat is the sensible heat of the drying medium at entry to the bed, although indirect heating of the medium by in-bed steam tubes has been used in some designs.

Fluid bed drying is well established for both batch and continuous processes. It is generally fast and efficient, and equipment size is relatively small compared with more traditional techniques, which in conventional designs results in low capital cost. In the case of continuous processes, beds are usually either the well-mixed type or the plug-flow type (Fig. 20). Well-mixed types are characterised by large
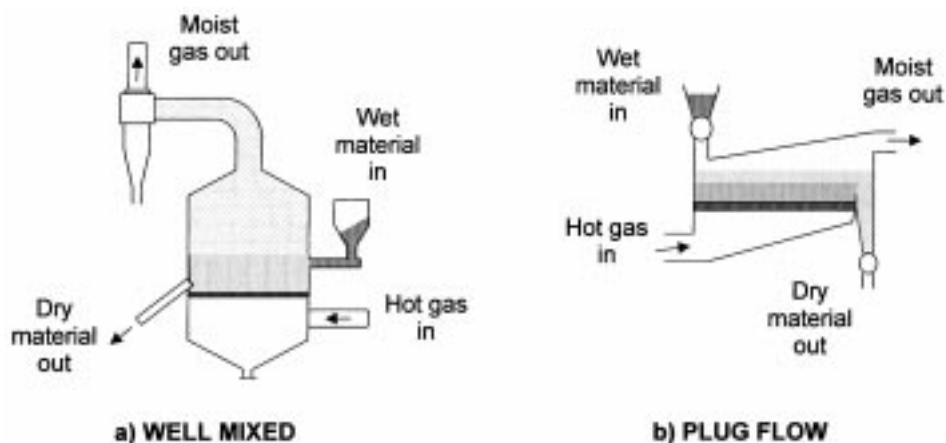

Fig. 20. Types of fluid bed dryer.

bed depth to width ratios and a large particle residence time distribution because of the highly vigorous mixing. In drying this implies a wide range of moisture contents, and plug flow designs with shallower beds in which the mixing is less vigorous are usually preferred. Material is admitted to one side of the bed and extracted from the other. Two or more bed chambers may be used in series to control the temperature/time history.

Because of the efficient heat transfer and mixing, the bed temperature is very uniform away from the immediate vicinity of the distributor plate through which the fluidising gas is admitted. This has two important consequences. Firstly, the temperature of the drying medium drops very rapidly from its inlet value to the bed value, so that high inlet temperatures can be used (up to 750°C with normal materials of construction) without the risk of exposing the material to such temperatures for more than very brief periods. Secondly, the temperature of the dried material leaving the bed and that of the exhausting gas is usually very similar.

Material size is an important consideration for fluid bed dryers. The material must be in a suitable form for fluidisation. This generally means particulate material of a reasonably small size (dependent to some extent on density) and a reasonably uniform size distribution. Fluid bed dryers have found widest application for particle sizes of less than 10 mm (usually significantly less)—often granular or crystalline materials with very uniform size. An average particle size of 10 mm has been suggested as the upper limit [31].

Larger size materials can be dried successfully, although there are one or two potential problems the seriousness of which will be dependent on the specific material and end use. Higher fluidisation velocities are required for larger particles, and also longer residence times in order to complete the drying. This will increase the tendency to entrainment and carry-over of smaller particles, and as particle size increases the size range tends to increase also, compounding the problem. Fortuitously the particles that become entrained will tend to be the lightest and therefore the driest particles, so that carry-over can be viewed as a self-ejection mechanism which acts to prevent over-drying. Cyclone separation is nearly always necessary with this type of dryer (certainly for IGBP feedstocks), so the separated dry material could simply be added to the main material outlet stream. Also associated with larger particles is the phenomenon of channelling— the formation of large voids in the bed due to fluid dynamic instabilities. This is very much a function of the precise material and size distribution, and would need to be investigated experimentally. The relatively large mean size and wide size range usually associated with IGBP feedstocks must however make conventional fluid bed drying a problematic choice in most circumstances, despite the low capital cost.

Emissions such as blue haze would be controlled by selecting an appropriate bed temperature. Particulate emissions are more of a problem, and a second stage of dust removal may well be necessary beyond the cyclone stage (bag filter or scrubber) depending on local legislation.

5.5.1. Pressurised steam fluid bed dryer

A Danish company, Niro, has recently developed a unique and highly specialised design of pressurised steam fluid bed dryer specifically for moist fibrous particulate materials [32]. The system was designed primarily for the brewing, food and sugar processing industries, but at least two systems are in operation for the drying of wood chips with a mean particle size of up to 50 mm.

The dryer is shown in Fig. 21. Recycled moisture evaporated from the feed forms the low-pressure steam drying and fluidising medium. The bed of material is contained in 16 cells, arranged around a central high-pressure superheated steam heat exchanger. After leaving the cells the low-pressure steam passes through a cyclone for dust separation, after which the excess steam from evaporation is discharged, and the remainder passes down through the heat exchanger to be heated indirectly to about 200°C by the high-pressure steam (max. 25 bar g, 250°C), before returning to the bed distributor plates. The continuously discharged flow of evaporated steam is at about 2.8 bar g and 150°C, and may therefore be used as process steam elsewhere although it may require cleaning once condensed. The drying material passes through the 16 cells in sequence before being discharged from the last. Fines separated in the cyclone are passed directly to the final cell.

Niro claim a very efficient process because of the utilisation of the recovered steam, although a suitable external use must of course exist, as MVR for internal
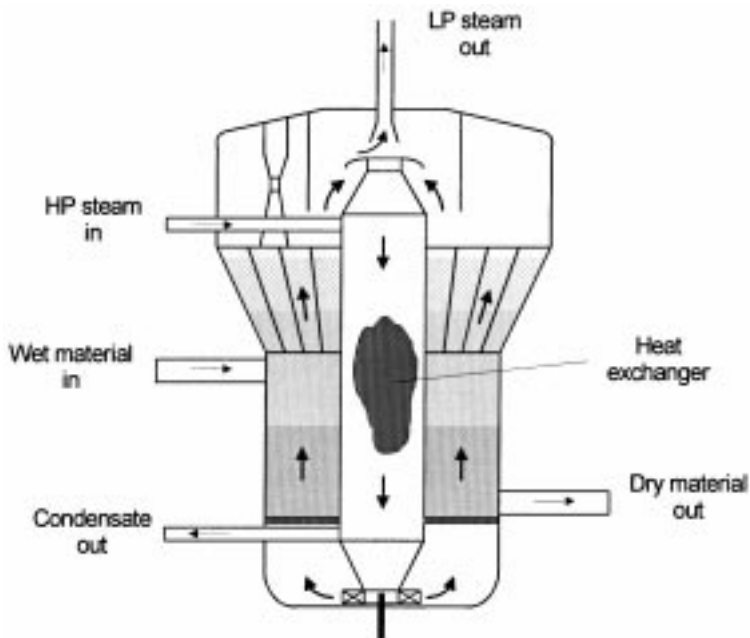

Fig. 21. Pressurised steam fluid bed dryer.

heat recovery is impractical with this configuration without major modifications. If the energy recovery is ignored, the thermal efficiency is around 70% if the high-pressure condensate is discharged, rising to well over 90% if the condensate is part of a closed high-pressure steam cycle. Almost all of the energy used to dry the material can be recovered.

Niro also claim excellent environmental performance as a result of the system being fully closed with no gaseous emissions to atmosphere.

The minimum size of dryer offered has a capacity at 25 bar steam pressure of 3 tonnes per h water evaporated, and the largest 40 tonnes per h. Niro have suggested 5 tonnes per h as a minimum for a viable installation drying wood chips [33].

Capital cost is high due to complexity of design, and the dryer is likely only to prove attractive for relatively large scale plant and where the full benefit of energy recovery can be realised. Table 5 gives typical performance data for the drying of wood chips for a plant size of about 50 MW thermal input.

5.6. Pneumatic conveying

Pneumatic conveying dryers achieve rapid drying with short residence times by fully entraining the material in a high velocity gas flow. The category is usually taken to include dryers where the entraining gas is combustion products or steam as well as air. Most pneumatic conveying dryer types can be dismissed for the present purposes because they require a fine particle size much smaller than would be suitable for most gasifiers or than could be economically prepared for IGBP feedstocks [34]. These include conventional flash dryers (Fig. 22)—very short residence time single-pass devices for removing relatively small amounts of moisture—and most ring dryers, in which the material is carried in an endless ring duct (Fig. 23).

Table 5
Pressurised steam fluid bed dryer performance data (Niro A/S)

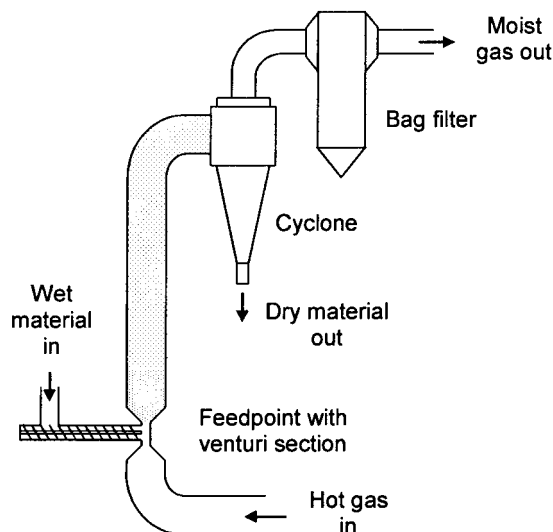| Material	Wood chips
Mass flow rate (dry), kg s^{-1}	2.5
Initial moisture content, % w/b	55%
Final moisture content out, % w/b	10%
Drying medium	Recycled LP steam
LP steam mass flow rate out, kg s^{-1}	2.78
LP steam temperature out, °C	150
LP steam pressure, kPa	300
Heating medium	HP steam
HP steam mass flow rate, kg s^{-1}	2.78
HP condensate temperature, °C	190
HP steam pressure, kPa	1400
Indicative capital cost, £000	1800

Fig. 22. Flash dryer.

A high-pressure steam flash dryer has been developed for IGBP feedstocks by IVO in Finland [35], but this is specifically intended for a pressurised fluid bed gasifier using very small particles of 2 to 3 mm diameter. One pneumatic conveying design related to the ring dryer has however been developed specifically for steam drying of biomass at particle sizes up to 50 mm maximum size, and this merits further description.

5.6.1. Pneumatic conveying pressurised steam dryer

A closed-loop pneumatic conveying dryer using only indirectly heated steam from the liberated moisture as the conveying and drying medium has been
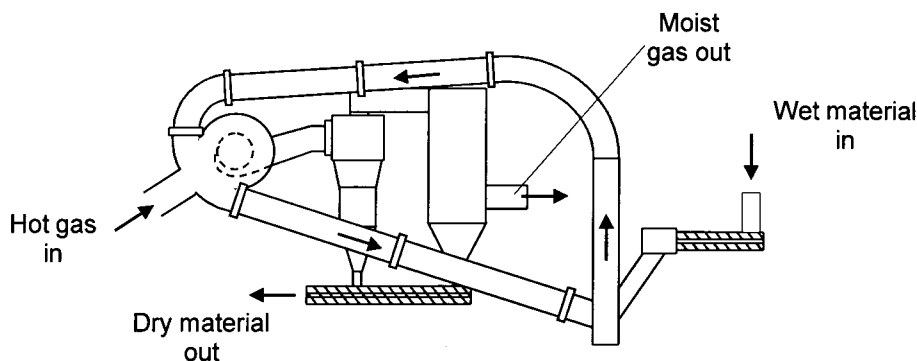

Fig. 23. Ring dryer.

developed in Sweden over a number of years by the Chalmers University at Gothenburg, the MoDo-Chemetics Company and Stork Friesland Scandinavia [36–38]. The technology, which was developed primarily for the wood products industry, is now owned and marketed as the 'Exergy' steam dryer by Stork Engineering.

The system layout is depicted in Fig. 24. The design philosophy has much in common with the Niro steam dryer (Section 5.5), including a high degree of energy recovery and zero gaseous emissions. The drying section consists of a sequence of vertically orientated shell-and-tube heat exchangers, through which the material is conveyed and the liberated steam superheated indirectly, usually by high-pressure saturated steam although combustion products or thermal oil can also be used. In the case of high-pressure steam, the heat exchangers are designed to be fully condensing. The number of stages depends on the degree of drying required. The dried material is extracted in a cyclone at the end of the heat exchanger train, and the near-saturated steam continues around the loop to a steam extraction point where the excess is continuously bled off at between 2 and 6 bar, available for external use. The remainder of the steam continues to a first stage of superheater before reaching the material inlet point and re-entering the drying section. Typical residence time of material in the dryer is 10 to 30 s, and a high level of uniformity in final moisture content is achieved.

Figures given imply a thermal drying efficiency (excluding recovery) of about 75% where the heating steam condensate is discharged, rising to 95% where the condensate is part of a closed steam cycle [39]. Standard units using 10 bar steam as the heating medium are offered at sizes from 0.25 to 5 tonnes of water evaporated per hour, but these are designed for fine materials such as wood shavings, sawdust, sludge, etc. with a high initial moisture content. Much larger units have however been supplied specifically for forestry wastes including wood
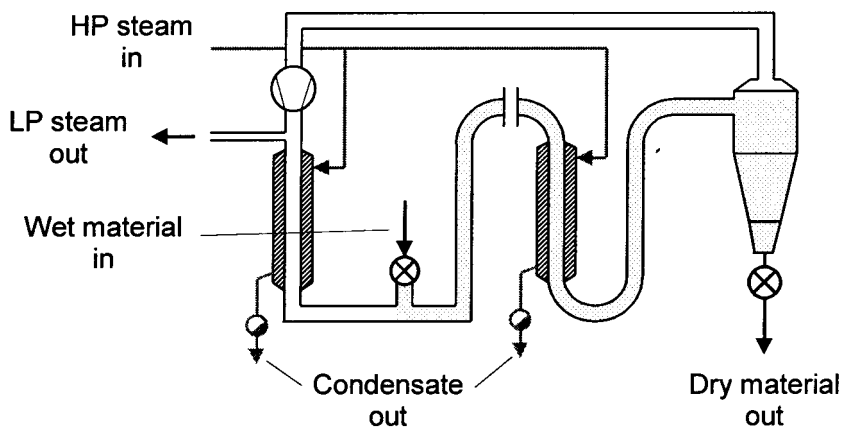

Fig. 24. 'Exergy' steam dryer (Stork Engineering).

Table 6
'Exergy' steam dryer process data

Plant	Skellefteå Kraft	Example B
Evaporation capacity (t/h)	22	12.5
Inlet moisture (% w/b)	55	60–70
Final moisture content (% w/b)	13	5–20
HP steam pressure (bar)	26	12
LP steam pressure (bar)	4.2	6.5

chips of up to 50 mm, with the objective of producing wood fuel pellets. Process data for two such plants is given in Table 6; unfortunately cost information has not been provided.

The process configuration is well suited to the application of MVR (Fig. 4), and an MVR option for internal heat recovery is offered by Stork for cases where there is no external use for the extracted steam.

5.7. Summary of drying options for integrated gasification bio-energy plant feedstocks

Table 7 gives a summary of drying options for IGBP feedstocks. All of the listed types have been used successfully in the past either for IGBP feedstocks or for materials sufficiently closely related for the extrapolation to be made. All have particular advantages and disadvantages, and their respective suitability will depend on the particular feedstock and various other features of the bio-energy plant in question, not least the scale.

6. Conclusions

1. The drying of biomass feedstocks to gasification is usually desirable and sometimes essential, in order to ensure satisfactory gasifier operation and improve product gas quality.
2. Key determinants in the choice of dryer are cost, capacity range, available sources of heat, alternative uses of that heat, avoidance of excessive material temperatures to prevent thermal degradation, avoidance of fire or explosion hazards.
3. Dryer types suited to integrated gasification bio-energy plants are perforated floor bin, band/conveyor, rotary louvre, rotary cascade, rotary steam tube, atmospheric fluid bed, pressurised fluid bed, pressurised pneumatic conveying.
4. Each of the listed dryer types has particular advantages and disadvantages. Final choice of dryer will follow careful technical and economic evaluation of the specific bio-energy plant under consideration. However, far more

Table 7
Summary of suitable dryer types for IGBP feedstocks

Dryer category	Dryer type	Comments re use with IGBP feedstocks
Batch through-circulation	Perforated floor bin or silo	Low cost, uses low-grade heat, but wide variations in final moisture content, final storage period required, extent of drying limited, batch system. Attractive at small scales.
Continuous through-circulation	Band	Highly controllable, can employ internal indirect heating so emissions moderate to low, but best suited to fragile materials.
	Rotary louvre	High heat transfer rates, higher specific throughput than rotary cascade dryers but more expensive, best suited to fragile materials.
Direct rotary	Rotary cascade	Uses large quantities of drying medium, emissions problems, but low-risk, reasonably economical and often used already at medium to large scales.
Indirect rotary	Rotary steam-tube	More expensive than rotary cascade, low emissions, best suited to materials which cannot be directly exposed to hot gases.
Fluid bed	Conventional once-through	Low cost, efficient heat transfer, but could be bed instability problems—only appropriate for relatively small mean sizes and narrow size ranges.
	Pressurised recycled steam	Purpose designed for integrated biomass plants, very expensive but could be economical at larger scales if recovered energy can be utilised. Very low emissions.
Pneumatic conveying	Pressurised recycled steam	Purpose designed for integrated biomass plants, expensive but could be economical at larger scales if recovered energy can be utilised. Very low emissions.

manufacturers are willing to offer rotary cascade dryers for IGBP feedstocks than any other type.

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